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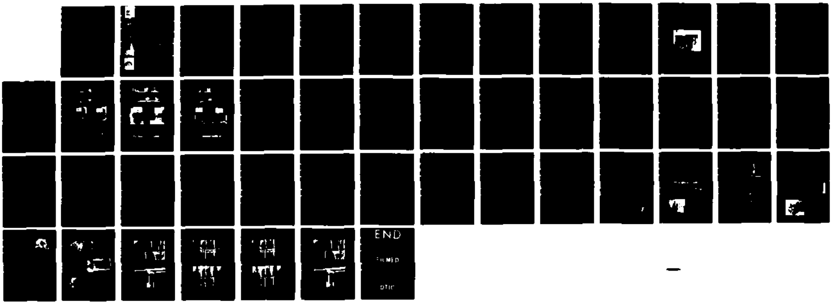

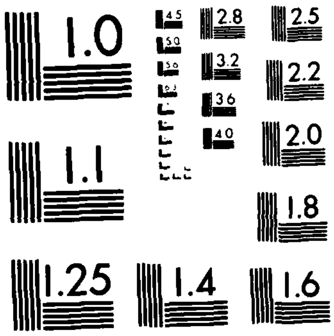

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TECHNICAL REPORT NO. 6-570

DURABILITY AND BEHAVIOR OF PRESTRESSED CONCRETE BEAMS

Report 6

POSTTENSIONED CONCRETE BEAM INVESTIGATION, SUPPLEMENTAL LABORATORY TESTS OF BEAMS EXPOSED FROM 1961 TO 1982

by

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October 1984
Report 6 of a Series

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This report is the sixth in a series describing a study being conducted to develop information on the durability of prestressed concrete beams. This phase of the study is concerned with field and laboratory testing and with observation of posttensioning systems including end anchorages, end anchorage protection, posttensioning conduit, and posttensioning wires.

In June 1961, 20 air-entrained, posttensioned concrete beams were placed at the Treat Island, Maine, exposure station. The beams (Continued)

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were fabricated using four different types of posttensioning systems with 12 different types of end anchorage protection over external and flush anchorages. End anchorage protection was attached to the beams using six different types of joint preparation: bush-hammering, epoxy adhesive on sandblasted surface, retarding agent, sandblasted, sandblasted with primer, and no preparation. The end protections were made from three different mixtures: portland-cement concrete, epoxy concrete, and sand-cement mortar.

Since June 1961, the beams installed at mean-tide level at Treat Island have undergone twice daily tidal inundations and an average of 129 cycles of freezing and thawing each winter. While not immersed in seawater, the beams did not ever get more than surface dry. Eight beams were returned to the Waterways Experiment Station (WES) for autopsy and testing in September 1973 and December 1974. These beams were tested to determine the effects of the severe environment described above on the posttensioning system. The results were given in Technical Report 6-570, Report 4, "Durability and Behavior of Prestressed Concrete Beams; Posttensioned Concrete Beam Investigation with Laboratory Tests from June 1961 to September 1975."

In January 1983, three more beams were returned to WES from Treat Island for autopsy and additional testing. The results of these additional tests are the subject of this investigation. The testing included (a) structural testing, visual evaluation of beam condition, and autopsy of the beams subsequent to testing; (b) visual evaluation of the end anchorages and posttensioning conduit; (c) autopsy of the posttensioning systems; (d) analysis of the products of corrosion on the posttensioning wires; and (e) determination of thermal expansion of the concrete of the beam and of the epoxy concrete and caps.

If no further tests are made on the nine posttensioned beams that remain at Treat Island, this report will be the final report in the series.

PREFACE

The study reported herein forms a part of Engineering Study 031 (formerly Civil Works Investigation Item CW 031) and was authorized by multiple letter dated 11 December 1956 from The Office, Chief of Engineers (HQUSACE). The project plan, "Durability and Behavior of Prestressed Concrete Beams," was drafted in accordance with instructions from HQUSACE and recommendations of the Reinforced Concrete Research Council (RCRC) of the American Society of Civil Engineers (ASCE).

The exposure program was planned by HQUSACE in cooperation with the RCRC of ASCE. The test program was coordinated with the RCRC and carried out by the Structures Laboratory (SL), Waterways Experiment Station (WES), US Army Corps of Engineers, under the direction and supervision of Messrs. Bryant Mather, Chief SL; John M. Scanlon, Jr., Chief, Concrete Technology Division; and James E. McDonald and Henry T. Thornton, Jr., former Chief and Chief, Evaluation and Monitoring Group. The Project Leader was Mr. Edward F. O'Neil. This report was prepared by Messrs. Glenn L. Odom and O'Neil.

Commanders and Directors of WES during the study and the preparation and publication of this report were COL A. P. Rollins, Jr., CE, COL E. H. Lang, CE, COL A. G. Sutton, Jr., CE, COL J. R. Oswalt, Jr., CE, COL L. A. Brown, CE, BG E. D. Peixotto, CE, COL G. H. Hilt, CE, COL J. L. Cannon, CE, COL N. P. Conover, CE, and COL T. C. Creel, CE. Technical Directors were Messrs. J. B. Tiffany and F. R. Brown.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
gallons (U. S. liquid)	3.785412	litres
cubic yards	0.7645549	cubic metres
inches	25.4	millimetres
pounds (force)	4.448222	newtons
pounds (force) per minute	0.07413703	newtons per second
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.45359237	kilograms
tons (2000 lb force)	8.896444	kilonewtons

* To obtain Celsius (C) readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

DURABILITY AND BEHAVIOR OF PRESTRESSED CONCRETE BEAMS

POSTTENSIONED CONCRETE BEAM INVESTIGATION, SUPPLEMENTAL LABORATORY TESTS OF BEAMS EXPOSED FROM 1961 TO 1982

PART I: INTRODUCTION

Background

1. In June 1961, 20 air-entrained concrete beams were placed at the Treat Island, Maine, exposure station. The beams were subjected to tidal inundations twice a day and to an average of 129 cycles of freezing and thawing per year. Each beam was 96 in.* long and had a cross section of 10 by 16 in. with a 68-in.-long thin web section where the cross section was 5 by 6 in. The beams were cast around four different types of posttensioning systems with 12 different types of end anchorage protection over external and flush anchorages. End anchorage protection was attached to the beams with one of four different types of joint preparation. Tables 1-4 present the physical properties of the beams and describe the end anchorages and protective systems.

Purpose of Investigation

2. The purpose of the investigation was to test and evaluate prestressed concrete beams and various types of end anchorage protection exposed to long-term weathering. This was accomplished through observations, structural testing, and physical analysis of eight beams returned in the previous investigation and three posttensioned beams evaluated in this investigation. These three beams were returned to the Waterways Experiment Station (WES) in January 1983. The reasons to return additional beams were to investigate causes of corrosion to the posttensioned wires and the conventional stirrup reinforcement after an additional nine exposure seasons, as well as investigate the cause of deterioration to the joint between epoxy end caps and the concrete on several of the beams.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

Scope of Investigation

3. The laboratory tests consisted of the following procedures:

   a. Initial observation and photographic recording of the as-received condition of the beams.

   b. Thermal expansion testing of the portland-cement concrete and epoxy concrete in beam 20.

   c. Destructive testing of each beam to determine short-term load-deflection characteristics, the load at initial cracking, the crack pattern history, the ultimate flexural load, and the type of beam failure.

   d. Observation of corrosion on the conventional reinforcement to include special observation of the stirrups in the vicinity of the web of the beam and of the condition of the posttensioning system.

   e. Internal observations of the conduit, grout, and wires of the posttensioning system.

   f. Comparison of the expansion properties of the portland-cement concrete and epoxy concrete in beam 20.

PART II: TESTING PROCEDURE

4. The as-received condition of each beam was recorded by means of photographs taken of the landward and seaward ends and the sides of the beams. Observations were recorded on the physical condition, spalling, cracking, rust staining, and exposure of the reinforcing steel for each beam.

5. After being photographed, the beams were marked for third-point structural testing and loaded into the testing frame (Figure 1). The protective end caps were not included in determining the testing span. The support markings were placed 6 in. from the end of the beam proper except for beam 4. Spalling on one end of beam 4 necessitated placing the supports 9 in. from each end of the beam proper.

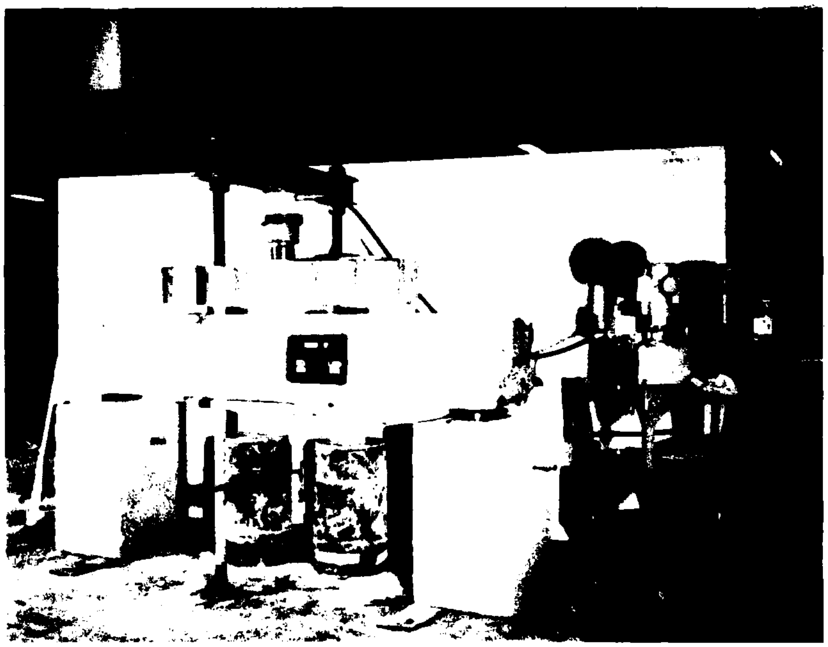


Figure 1. Test apparatus

Loading

6. Load was applied to each beam with a 60-ton hydraulic ram at a constant rate of approximately 2049 lb force per minute. Deflection readings, taken to the nearest thousandth of an inch, and elasped time were recorded at approximately each 2049-lbf increment. Cracks were marked as loading progressed,

with photographs taken at periodic points to record crack pattern growth. Failure condition was recorded with photographs, and the type of failure noted.

Autopsy of the Beams

7. The concrete of the beams was removed using an air hammer. When all concrete was removed, observations were made and photographs taken of the conventional reinforcing cage and posttensioning system. The degree of corrosion on the end anchors and outside surface of the conduit was recorded.

8. Upon removal of the posttensioning system from the reinforcing cage, an abrasive grinding wheel was used to open the conduit and expose the grout and posttensioning wires. Observations were made and photographs were taken as the conduit was spread open and the wires removed. Each individual wire was labeled and the amount of corrosion on the surface area recorded. The corrosion was described as light, moderate, or heavy, depending on the percentage of surface area covered, using the rating scheme that was described in Report 4 of this series (O'Neil 1977).

9. The surface corrosion on the wires was then removed with sandpaper in order to measure the diameter of the uncorroded wires. The diameter was measured with a micrometer. Five points along each wire were measured including both ends and fourth-point intervals along the wires.

Thermal Expansion Testing

10. Before beam 20 was structurally loaded, a thermal expansion test was performed to record expansion and contraction of both epoxy concrete end caps and the portland-cement concrete of the beam to which the caps were attached. Four pairs of 1/4-in.-diam anchors were embedded in the surface of each end of the beam and then center-punched to serve as reference points. Two of the pairs were embedded in each end cap, and two of the pairs were embedded in each end of the beam itself. The anchors in each pair were set approximately 2 in. apart. The pairs of anchors were located approximately 1 in. on either side of the joint between the end caps and the beam proper and approximately 3 and 10 in. from the top edge of the beam. (Figure 2 shows the relative location of the anchor pairs.) Measurements were made with a 2-in.-long Windsor gage read to the nearest 0.00005 in.

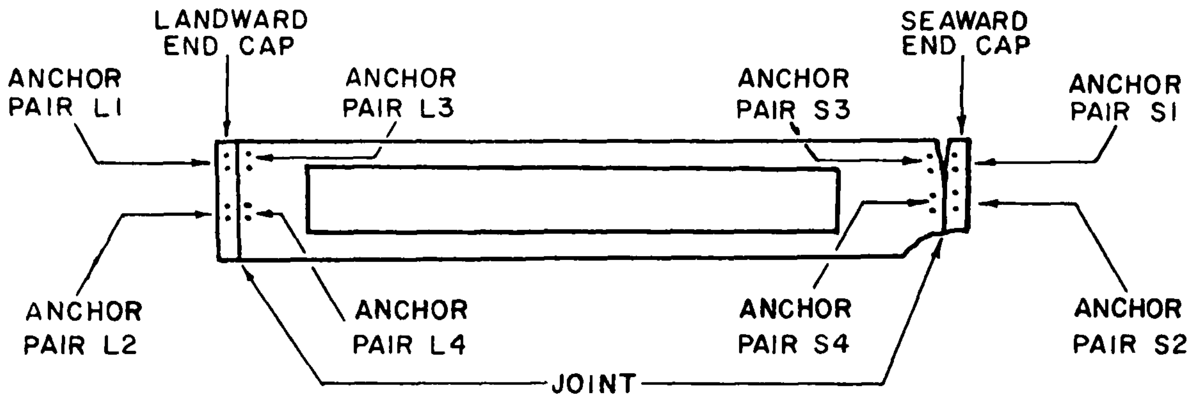


Figure 2. Locations of anchor pairs

11. Baseline readings of all the anchors were made at room temperature, and the beam was then placed in a controlled-temperature room and put through two cycles of temperature change from 40° F to 120° F. For each cycle, the temperature in the room was initially set at 40° F, and measurements were taken twice daily until no more decrease in gage reading was observed. The temperature was then raised to 120° F and gage readings again taken until no further increase in readings was observed.

PART III: OBSERVATIONS AND TEST RESULTS

12. The tests and observations conducted in the laboratory investigation were performed on beams 4, 17, and 20. Tests were conducted to observe any additional deterioration of the beams that may have occurred during the years since the last autopsy report (O'Neil 1977). Observations of deterioration and corrosion were made for each beam, the posttension anchorages, the outside and inside of the posttensioning conduits, and the posttensioning wires. In addition, the thermal expansion tests were conducted to determine the degree of difference in thermal expansion that exists between the epoxy concrete end cap and the portland-cement concrete beam. This was done to judge if differential expansion could be a contributive cause of deterioration of the joint between epoxy concrete end caps and the concrete beam.

13. In the evaluation of the extent of corrosion of the steel and conduit, the procedure described in paragraphs 28 and 29 of Report 4 was used. Corrosion was categorized as light, moderate, or heavy depending on the amount of surface area covered. The three types of corrosion categorized in Report 4 (rusting, pitting, and tarnishing) are described in paragraphs 29-31 of that report.

14. In order not to be misleading, some explanation of the system of identifying the degree of corrosion must be made. Although corrosion described as heavy means that 80 percent or more of the surface area is covered by corrosion, this does not mean that 80 percent of the cross section had been corroded away; only that surface rust covered 80 percent of the surface of the steel. Actually, no steel wires observed showed any deep corrosion or deterioration, although some deterioration was observed for the end anchorages.

Structural Testing

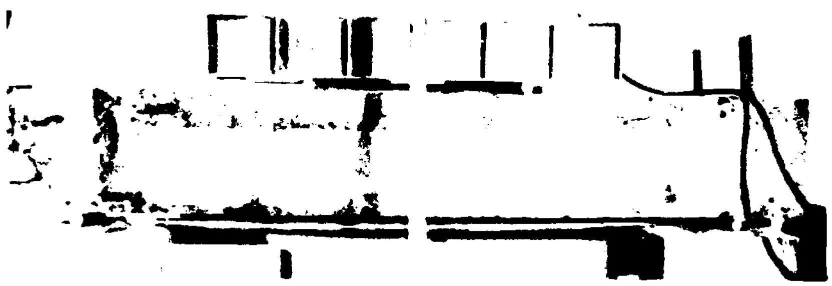
15. When the three beams were tested in third-point loading, all showed similar crack patterns as load increased. First cracks began to appear between 44,400- and 50,500-lbf loads for the three beams. The three beams failed in flexure with the concrete failing by crushing in the compression zone (Figures 3e, 4e, and 5e). Failure loads and deflections for beams 4, 17, and 20 were 75,114 lbf and 0.650 in., 101,751 lbf and 0.520 in., and 92,184 lbf and 0.655 in., respectively.

a. Side view

b. Side view

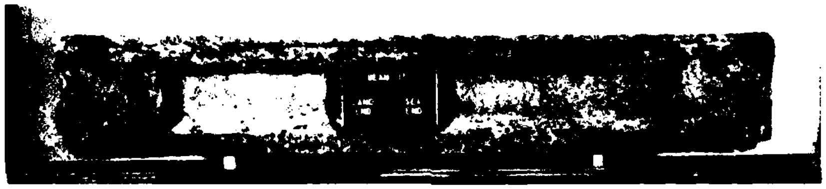
c. Landward end view

d. Seaward end view

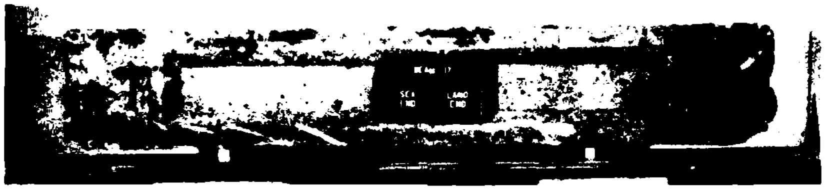


e. Failure condition

Figure 3. As-received and failure conditions of beam 4



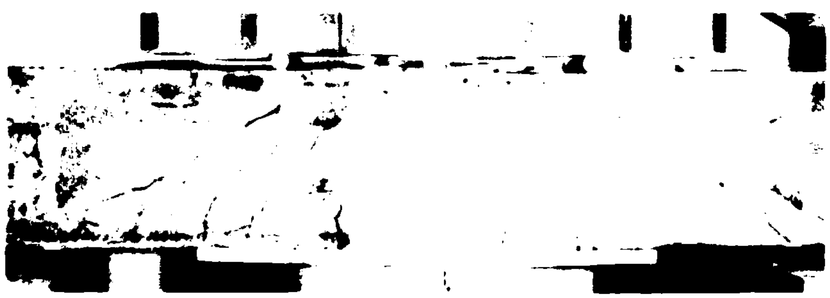
a. Side view



b. Side view

c. Landward end view

d. Seaward end view



e. Failure condition

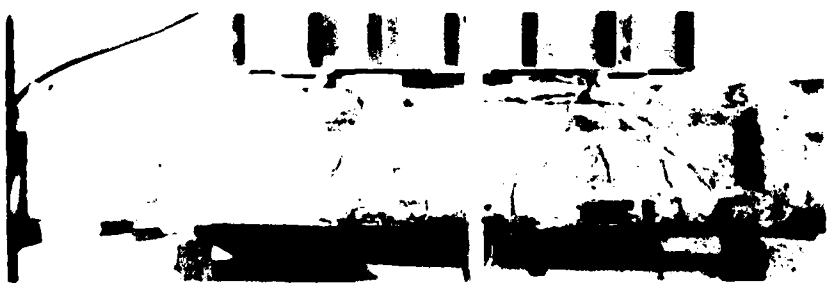
Figure 4. As-received and failure conditions of beam 17

a. Side view

b. Side view

c. Landward end view

d. Seaward end view



e. Failure condition

Figure 5. As-received and failure conditions of beam 20

Thermal Expansion Test

16. The thermal expansion test performed on beam 20 yielded average values for thermal expansion for the epoxy concrete end protective cap on the seaward and landward ends of $19.8 \times 10^{-6}/^{o}$ F and $6.2 \times 10^{-6}/^{o}$ F, respectively, while the average values for the concrete beam on the seaward and landward ends were found to be $5.1 \times 10^{-6}/^{o}$ F and $4.6 \times 10^{-6}/^{o}$ F, respectively. The results are shown in Table 5.

Beam 4

17. The as-received condition of beam 4 is shown in Figure 3. Concrete had spalled on some edges exposing the conventional reinforcement to attack by seawater. Sixty percent of the conventional reinforcement was exposed on one top edge. Several small places on the other top edge and one bottom edge showed exposed reinforcement. The exposed reinforcement on the seaward end, bottom edge, was corroded completely through. All exposed reinforcement was heavily rusted and deteriorated. The lower half of the seaward end had spalled from the end of the beam, exposing part of the epoxy concrete end protective plug and end anchor. The plug covering the end anchorage was still in place over the end anchor. At the landward end, there was a 1/2-in.-wide by 1/2-in.-deep gap between the beam and the end cap. Otherwise, the landward end epoxy concrete cap was in good condition.

Condition of landward end anchorage

18. Very little corrosion had taken place on the 1-1/2 in. of wire protruding from the end of the anchorage (Photo 1). Only light tarnishing was observed. The steel coil of wire surrounding the concrete of the Freysinnet anchor had light rust covering less than 1 percent of the surface area. The mortar within the coils was dense and solid.

Condition of the conduit

19. The outside of the conduit was lightly rusted. The rust was located in small patches along the length of the conduit. Less than 1 percent of the surface area was covered by rust. The conduit was divided into alternate and irregular lustrous and tarnished areas.

20. The inside of the conduit showed light surface rust concentrated along the length of the bottom of the conduit. The sides and top of the

conduit showed mixed areas where the conduit appeared tarnished or lustrous, similar to the appearance of the outside of the conduit.

Condition of the wires

21. Observations of the 12 posttensioning wires showed that approximately 80 percent of the length of the wires was lightly to moderately rusted, pitted, and tarnished. The heavy rust was located along the middle 20 in. of the wires. Many of the wires had streaks of rust where they appeared to have been touching one another. Streaks of rust were found on both ends of five of the wires and only on the landward ends of three other wires. The length of the rust streaks varied from a few inches to 23 in. No deep corrosion was found on any of the 12 wires.

Condition of the seaward end anchorage

22. The 1-1/2 in. of posttensioning wires protruding from the end of the seaward anchorage had heavy rust covering 100 percent of the surface area (Photo 2). All wires appeared to have lost some of their cross-sectional area. The greatest corrosion occurred where the wires entered the steel confining coil of the end anchor. The anchorage on that face was badly rust-stained from the corrosion of the wires. The steel coil of wires on the other hand was found to be only lightly tarnished.

Beam 17

23. The "as-received" condition of beam 17 is shown in Figure 4. The concrete was spalled away at the edges on much of the beam, exposing the conventional reinforcement. On one side of the beam, the top edge had reinforcement exposed the whole length of the beam proper. The bottom edge had exposed reinforcement in two small spots. The exposed reinforcement was badly deteriorated. The steel exposed on the bottom edge of the landward end had been completely corroded through its cross section. Both protective end caps were missing, exposing the end anchorages to seawater. The concrete along the edges had spalled, exposing conventional reinforcement on both edges of the landward end of the beam and on one edge of the seaward end.

Condition of landward end anchorage

24. The outside face of the landward anchorage was heavily corroded (Photo 3). The anchorage was covered with unsound, rusted metal that was flaking off in pieces 1/8 in. thick, leaving sound but heavily rusted metal

underneath. The inside face was lightly rusted with a small amount of thin rusted steel flakes separated from the surface.

Condition of the conduit

25. The outside of the funnel housing at the landward end had a few small rust patches scattered around the surface area. The inside of the funnel housing was found to have rust concentrated at the bottom of the housing in two parallel streaks approximately 2 in. apart, with scattered areas of rust between (Photo 4). The remainder of the landward funnel housing was heavily pitted.

26. The outside of the conduit also had light patches of surface rust scattered along its length. The conduit was divided into three separate sections. The two outer sections appeared lustrous over much of the surface area. The middle section was much more tarnished. Large patches of rust were found on the areas where tape was used to connect the three sections of conduit together. The inside of the landward section of conduit was moderately rusted toward the landward anchorage decreasing to rust covering less than 1 percent of the surface area toward the middle section of conduit. The inside of the middle section was not rusted but was heavily tarnished. The inside of the seaward section appeared similar to the inside of the landward section. However, the bottom of the conduit had surface rust beginning at a point about 1 ft from the seaward end widening to a width of about 1 in. toward the seaward end and extending into the funnel housing (Photo 5).

27. The seaward end funnel housing was heavily rusted on the outside surface with one small area on the bottom side where steel was corroding in flakes (Photo 6). The inside of the housing had two streaks of rust, each 1/2 in. wide, extending along the bottom side (Photo 7). Otherwise the housing was heavily pitted.

Condition of the wires

28. Most of the 12 posttensioning wires were lightly to moderately corroded along all of the seaward half and on 65 percent of the landward half. The heaviest rusting occurred within 15 in. of the landward end of the wires (Photo 8). All 12 wires were described as heavily rusted on the outermost 15 in. of their landward end. Two wires were described as heavily rusted from 3 in. to about 15 in. along their seaward end. Streaks of rust from 3 to 15 in. long where wires appeared to have been touching each other were found on 6 of

the wires at the seaward end; an 18-in. streak was found on one of the landward ends. No significant deterioration of the wires was observed.

Condition of the seaward anchorage

29. The surface of the outside face of the seaward anchorage was heavily corroded (Photo 9). Portions of this anchor were deteriorated to the point of metal flaking from the rest of the anchor. The inside face of the seaward anchorage was similar to that of the landward anchorage, with heavy cover of rust but no severe loss of metal area.

Beam 20

30. The "as-received" condition of beam 20 is shown in Figure 5. Concrete was spalled away at the edges on much of the beam exposing some conventional reinforcement. On one top edge, the reinforcement was exposed along the total length. Both bottom edges had some exposed reinforcement. All exposed reinforcement was heavily corroded. Reinforcement in one area on the bottom edge had been completely corroded through its entire cross section. The landward protective end cap was in place and in generally good condition. This epoxy concrete end cap was anchored to the beam through the aid of reinforcing bars that protruded from the end of the beam into the cap. The end cap was separated from the beam proper by a 1/2-in. gap that was 1/2 in. deep (Photo 10). The reinforcement that held the end cap to the beam at this end of the beam was heavily covered with rust. There were two pieces of reinforcement that connected the cap to the beam. One piece was not reduced in cross section by the corrosion, but the other was reduced at the point where the 1/2-in. gap occurred, until the diameter of the bar was only 3/16 in. The seaward epoxy concrete end cap was also in place, but 4 in. of the bottom of the end cap had spalled away. This end cap was also partially separated from the beam by a 1/2-in. gap that was 4 to 8 in. deep (Photo 11). This end cap did not have reinforcing bars anchoring the cap to the beam.

Condition of the landward end anchorage

31. The outside surface of the landward end anchorage was heavily rusted (Photo 12). A 1/16-in. layer of steel was flaking away on 90 percent of the anchor. The inside surface was lightly rusted and heavily tarnished. No deterioration of the steel was observed on this face of the anchor.

Condition of the conduit

32. The landward funnel housing was heavily corroded around the outside surface (Photo 13). The inside surface was lightly rusted on the bottom and heavily pitted on the sides (Photo 14). The remainder of the inside surface was lightly tarnished.

33. The conduit was divided into three sections. The outer two sections, one at the seaward end and one at the landward end, were both lightly rusted with spots scattered along the length of the conduit. The surface showed alternating areas of lustrous and tarnished finish. Less than 1 percent of the inside surface of these pieces showed rust. The appearance was mostly that of a lustrous finish. The larger middle section was moderately rusted and heavily tarnished (Photo 15). A few rusting areas showed flaking steel. The inside of the middle section was tarnished. Some of the joints in the corrugated conduit were rusted.

34. The outside surface of the seaward funnel housing was heavily corroded (Photo 16). The inside surface was rusted along the bottom (Photo 17). Two rust streaks 1 in. apart extended along the bottom of the housing. The remainder of the housing was moderately pitted.

Condition of the wires

35. The 12 posttensioning wires showed no signs of heavy rusting. Only light to moderate rusting, pitting, and tarnishing were noted. The degree of corrosion was observed to be generally moderate toward both the landward and seaward ends of the wires. The middle 50 to 60 in. showed light to moderate corrosion. No degree of deterioration was found.

Condition of the seaward anchorage

36. The outside surface of the seaward anchorage was heavily corroded (Photo 18). Small thin flakes of corroded steel were found over the entire surface. The inside surface area was heavily tarnished with no rusting except in two areas on opposite corners at manufactured threaded openings in the plate.

PART IV: SUMMARY OF OBSERVATIONS AND TESTS

Condition of End Anchorages

37. The condition of each end anchorage protection was visually determined either annually or biennially at the Treat Island exposure station. The condition of each protective cap or plug was adjudged by a panel of observers and given a numerical rating from 0 to 28 to describe its visual condition. A tabulation of the average rating for each of the 12 protective systems represented on the 20 beams installed at the exposure station for the years 1961 through 1975 is given in paragraph 168 of Report 4 of this series (O'Neil 1977). A rating of 0 coincides with an end protection in perfect condition, while a rating of 28 indicates an end protection in complete failure.

38. The three beams tested in this investigation represented five different protective systems. Beam 17 was protected by a Type 1 external concrete cap on the landward end of the beam and by a Type 3 external concrete cap on the seaward end.* The ratings for these end protective systems, as shown in Report 4, were the poorest of any of the protective systems studied. Review of the annual inspection reports indicates that these end caps began to fail in 1966. The failure of both end caps from beam 17 gives them a rating of 28, a rating consistent with the results found previously. Without their protective caps, the exposure of the outside of the anchors to seawater and air induced corrosion. The relatively less corroded condition of the inside face of the anchors on this beam would indicate that less seawater and air penetrated the concrete covering these areas.

39. Beam 4 was protected by a Type 7 external epoxy concrete end cap on the landward end and a Type 7 flush epoxy concrete plug on the seaward end. The average rating for both these protective systems in Report 4 was good. The anchorage beneath the landward end cap showed practically no signs of corrosion. This condition corresponds well with the good average rating given the end cap in the 1975 inspection, which would indicate that little if any air or seawater penetrated the end protective cap. The seaward end plug, while still in place, did not prevent seawater and air from causing heavy corrosion on the anchor. The concrete around the plug had separated, the area underneath the plug was

* A description of the end protection type and method of joint preparation is given in Table 2.

spalled and rust-stained. This condition would indicate that this plug did not provide the protection to the end anchorage that was anticipated, and the end deteriorated allowing continuous corrosion to the protruding anchor wires.

40. Beam 20 was protected by a Type 7 external epoxy concrete end protection cap on the seaward end of the beam and a Type 8 epoxy concrete external cap on the landward end. A Type 7 epoxy concrete external system was also on beam 4 and was shown to have provided good protection from corrosion even though the joint between the cap and beam had a 1/2-in.-wide, 1/2-in.-deep deterioration at the top. For beam 20, while the end cap was in place and appeared in good condition, observation of the steel of the end anchor after autopsy showed that heavy corrosion had taken place on the anchorage. Since the end cap was made of an epoxy concrete which contains no air void system, through which water and oxygen could travel, and since a small gap did exist along the top portion of the joint between the end cap and beam, it is assured that the bond between the beam and end cap was damaged and air and water entered along the joint between the end cap and the concrete beam causing heavy corrosion as indicated by corrosion stains located on the sides of the beam at the joint.

41. The Type 8 external system had a fairly good average rating in Report 4. However, on beam 20 in this report, while the end cap was in place, its lower 4 in. was spalled away exposing the bottom of the end anchor. Additionally, the top portion of the end cap was separated from the concrete beam by a 1/2-in.-wide by 4- to 8-in.-deep gap. This situation was probably caused by water collecting in the joint between the cap and beam on the top of the beam and then freezing. The freezing deteriorated the concrete at the joint thereby making a larger crack for water to collect in. Repetitive sequences of freezing and deterioration enlarged the crack and eventually allowed water to corrode the end anchor. When the products of corrosion were voluminous enough, they caused the spalling and allowed further corrosion.

Condition of the Reinforcing Stirrups

42. An objective of this investigation was to observe and report any corrosion on the conventional reinforcing stirrups. It was recently theorized by the Reinforced Concrete Research Council, Task Committee No. 6, that since the

cover over the tendons in the web area of the beam was smaller there would be more access of seawater to the tendon in this region, and a potential source of corrosion.

43. The reinforcing stirrups of beams 4, 17, and 20 all experienced some degree of corrosion. Basically the stirrups were only lightly corroded, with rust covering less than 10 percent of the surface area. The magnitude of the corrosion on the stirrups was no greater than that observed on the stirrups in the 1975 autopsy. Most of the corrosion was light surface rust, although beam 20 did have some areas that showed signs of deterioration. The corrosion was concentrated on the stirrups from the weld points to the longitudinal reinforcement and where the stirrups themselves were attached together (Photos 19-20). An attempt was made to correlate areas of rusted stirrups with any staining of the surface of the beam, and the result was that no rust stains on the surface of the concrete beam could be associated with any incidence of stirrup corrosion. Since most of the corrosion appeared at weld points, the process of welding the bars together may have changed the properties of the steel such that these areas were more susceptible to corrosion than areas that had not been heat-treated. Some spot corrosion was observed on the vertical sections of the stirrups (Photo 22), but this was only very light surface corrosion. The outsides of the conduits containing the posttensioning wires were also only lightly rusted. These observations indicate that, even though the concrete cover over the stirrups and the tendons was thin, the ingress of water, oxygen, and chlorine ion at the web section of the beam did not cause heavy damage to the stirrup reinforcement.

Condition of the Conduit

44. The conduits in the three beams tested in this investigation were described as lightly to moderately rusted with varying degrees of tarnishing. The conduits of beam 17 and beam 20 were in three separate sections connected with tape. The conduit of beam 4 was one piece.

45. The surface of the conduits of beams 17 and 20 was rusted and discolored where the tape joined the sections together. Beam 17 showed a 1-in.-wide streak of rust 1 ft in length at the end of the conduit extending into the funnel housing. All four funnel housings of these two beams showed similar streaks of rusting along the bottom of the inside surface. Water ponding

in these areas during fabrication of the conduit could have caused this light corrosion. Some light deterioration was observed in a few joints of the middle section of the conduit of beam 20.

46. With the light to moderate corrosion found on the three conduits of beams 4, 17, and 20 and that corrosion being in the form of mostly small rust spots scattered along the conduits, it was observed that no more corrosion was found on these beams than on those autopsied in Report 4.

Condition of the Wires

47. Each of the three beams in this investigation had 12 posttensioning wires in its conduit. Each wire was found to have varying degrees of corrosion along its length. The following paragraphs summarize the trends of the corrosion on the wires in each beam.

48. The wires of beam 4 had light to moderate rusting, pitting, and tarnishing over approximately 80 percent of their length. The heaviest rust was located along the middle 20 in. of the wires. No deep corrosion was found on any of these 12 wires. Micrometer readings found a loss in original diameter of only 0.004 in. No severe corrosion took place on the wires.

49. The 12 posttensioning wires of beam 17 had light to moderate corrosion along the whole seaward half and along 65 percent of the landward half. The heaviest rust was located on approximately the first 15 in. of the landward ends. No deterioration of the wires was observed. No loss in diameter was shown by the micrometer measurements.

50. The wires of beam 20 showed no signs of heavy rusting. Only light to moderate rusting, pitting, and tarnishing were recorded. Micrometer measurements showed no loss of cross section from the original diameter of the wires. No severe corrosion took place on these wires.

51. It was observed that the amount and degree of corrosion observed on the wires of the three beams autopsied in this investigation were no more severe than those observed on the wires and bars of the eight beams autopsied in Report 4. The heaviest occurrence of corrosion was found on the landward ends of the wires of beam 17 and the midsection of the wires of beam 4. As stated in Report, this corrosion was not detrimental to the structural capacity of the beam. The amount of corrosion found on the wires after 9 additional years of exposure indicates that no significant deterioration of the wires occurred during that period of time.

52. It has been suggested that the corrosion to the wires within the conduits occurred sometime in 1960 between the time when the conduit/wire assemblies were made and the time they were cast in the concrete beams (Schupack 1980). This hypothesis rejects the possibility of the corrosion occurring after the beams were placed at Treat Island. The general corrosion that was found on the wires after they were opened up in 1975 and 1983 could have occurred as is proposed by this hypothesis. The wires were not seen by anyone prior to being placed in the beams since they arrived at the WES already assembled in the conduits. However, during both autopsies, when the wires were examined, strips of rust heavier than general corrosion were found where two wires were found to be touching each other or where a wire was touching the inside of the conduit. This corrosion was referred to as contact corrosion. This contact corrosion occurred where wires were touching each other or the inside of the conduit only after they were posttensioned and the wires would not have been in that relative position prior to posttensioning or during the period between fabrication and placement in the beams. This is an indication that the contact corrosion took place after the beams were cast and the conduits grouted. This indicates that some of the wire corrosion occurred during the exposure period.

53. The hypothesis mentioned above could be the cause of the general levels of corrosion on the wires. It does not explain the occurrence of the contact corrosion. It is unfortunate that the condition of the wires inside the conduits at the time of placement in 1961 was not documented, however, at that time the issue of posttensioning wire corrosion was not a parameter of the testing program.

Thermal Expansion

54. The results of the thermal expansion tests done on beam 20 showed that there was a difference in expansion between the concrete beam and the epoxy concrete end caps. The thermal expansion in the epoxy concrete cap was approximately 4 times greater on the seaward end and 1-1/2 times greater on the landward end than the expansion of the concrete beam. This difference in expansion characteristics could cause bond to break between the beam and end cap. The upper portions of both end caps on beam 20 were separated by a gap 1/2 in. wide with the depth of the land end gap 1/2 in. and the depth of the sea end gap 4 to 8 in. This was caused by concrete deterioration at the interface as

discussed in paragraph 41. Once an initial gap is created, additional deterioration of the joint between the beam and the cap could be aided by water freezing in the opening created and expanding, thus further deteriorating the joint. On beam 20, the expansion was greater on the seaward end of the beam than on the landward end. This result was due to the fact that the seaward end beam-cap interface was more heavily deteriorated allowing the two materials greater freedom of movement. At the landward end, the bond between concrete and epoxy was apparently still intact over most of the joint; thus, the concrete somewhat restrained the epoxy expansion. At the seaward end, since the joint was deteriorated to a depth of as much as 8 in., the two materials were free to expand at their own rates. An additional factor in the deterioration of the joint is believed by some technologists to be related to critical saturation of the concrete adjacent to the epoxy concrete end cap. If the concrete is saturated in this area and then freezes, the water must expand, but cannot enter into the epoxy concrete and as a result further ruptures the concrete and contributes to the bond failure. It should be pointed out that the epoxy concrete cap bonded to the landward end of beam 4 was exposed to the same environmental conditions as beam 20 and it did not delaminate as did the seaward end of beam 20.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

55. Three posttensioned beams were returned to WES from Treat Island. After having been subjected to twice daily tidal inundations and an average of 129 cycles of freezing and thawing per year from June 1961 to December 1982. The beams were evaluated to determine the extent of corrosion that had taken place. The following paragraphs present the conclusions of this investigation.

56. The conventional reinforcing stirrups of the beams were evaluated to determine degree of corrosion and whether any pattern of corrosion existed. The stirrups were found to be only lightly corroded. Less than 10 percent of the surface area of these bars had any rust at all. The rest of the surface was unrusted. There was rust on the stirrups at most locations where the stirrups were welded to the longitudinal reinforcement and at points where they were welded to each other. The amount of rust that occurred at areas where no welding had taken place was minor and showed no pattern of occurrence. An attempt was made to match corrosion on the stirrups with rust staining found on the web of the beams, but no pattern could be discerned. Further, the outsides of the metal conduits of all three beams were only rusted to a minor degree when compared to the conventional longitudinal reinforcement. Therefore, it is concluded that the amount of water, oxygen, and chloride ion permeating the concrete in the web of the beam was not significant enough to cause any major corrosion to the stirrups, the conduit, or the prestressing steel.

57. Each wire of each beam was rusted to some degree. In general, corrosion was not concentrated on the ends of the wires which would indicate seepage of water through the anchorage system. In beam 17, there were more corrosion products on the landward end of the wires then elsewhere, however, the overall amount of corrosion found on the wires in the beams of this investigation was no heavier than that found on the wires in the previous laboratory autopsy. It is therefore concluded that, as a result of nine additional seasons of exposure, the level of corrosion to the wires was no greater than that found in the autopsy described in Report 4 of this series.

58. Results of the thermal expansion testing conducted on beam 20 showed that a difference in thermal expansion exists between the epoxy concrete end cap and the concrete beam. The difference in expansion between the seaward end

cap and the concrete beam was greater than the difference in expansion for the landward end cap and concrete beam. This variance was due to the fact that the bond in the landward end joint between the end cap and concrete beam was mostly intact while the concrete interface at the joint on the seaward end between the end cap and concrete beam was deteriorated to the point where there was a 1/2-in.-wide gap 4 to 8 in. deep. The respective materials of the seaward end cap and concrete beam were allowed to move independently of each other, while the bond on the landward end between the end cap and concrete beam appeared to influence the amount of expansion taking place.

59. The difference in expansion between the epoxy and the concrete was significant enough to put the joint between the two materials in a high state of stress. Therefore, it is concluded that differential thermal expansion is a plausible contributing cause of bond failure between the epoxy concrete end caps and the concrete beams. However, it is also felt that deterioration of the interface through freezing and thawing of the portland cement concrete also contributed to the bond failure.

Recommendations

60. From the observations made and data gathered in the posttensioned concrete beam investigation (Roshore 1961, 1967; O'Neil 1977) and the results of this investigation, it is considered that further study of the posttensioned beams would not yield more pertinent information concerning corrosion of the posttensioning systems.

61. The remaining beams should be left at the exposure station to continue to weather.

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O'Neil, E. F. 1976. "Durability and Behavior of Prestressed Concrete Beams; Laboratory Tests of Weathered Pretensioned Beams," Technical Report No. 6-570, Report 5, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

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Schupack, M. 1980. "Behavior of 20 Post-Tensioned Test Beams Subject to up to 2200 Cycles of Freezing and Thawing in the Tidal Zone at Treat Island, Maine," Publication SP-65-9, <u>Performance of Concrete in Marine Environment</u>, American Concrete Institute, pp 133-152.

Table 1

Mixtures Used to Fabricate Posttensioned Beams

A. Beams Proper (excluding the grout and anchorage protection)

Cement	Nominal Maximum Size Aggregate in.	Air Content %	Water-Cement Ratio (by Wt)*	Slump in.	Cement Factor bags*/cu yd	Nominal Compressive Strength psi (28-day Age)
Type III (high-early-strength)	3/4	4.0-5.0	0.52 (5.85 gal/bag)	1-1/2 to 2	5.98-6.05	6000

B. Anchorage Protection (excluding epoxy mixture)

Cement	Nominal Maximum Size Aggregate in.	Air Content %	Water-Cement Ratio (by Wt)*	Slump in.	Cement Factor bags*/cu yd	Nominal Compressive Strength psi (28-day Age)
Type III (high-early-strength	3/4	3.5-5.0	0.80 (9.03 gal/bag)	1-1/4 to 2	3.90-3.96	3000

C. Epoxy Concrete Protection

Cement	Nominal Maximum Size Aggregate, in.	Mixture Proportions (by Wt) Epoxy Binder:Sand:Coarse Aggregate	Compressive Strength, psi (28-day Age)
None	3/4	2.83:7.00:10.00	9,320-11,320

D. Mortar Mixtures

Cement	Nominal Maximum Size Aggregate, in.	Water-Cement Ratio (by Wt)*	Cement Factor bags*/cu yd	Compressive Strength, psi (28-day Age)
Type III (high-early-strength)	100% passing No. 4 sieve	0.44 (4.95 gal/bag)	10.90	7710-7800

(Continued)

Table 1 (Concluded)

E. Grout Mixtures

Cement	Water-Cement Ratio (by Wt)*	Compressive Strength, psi (7-day Age)	Linear Expansion, % (3-day Age)
Type III (high-early-strength)	0.40-0.49 (4.51-5.53 gal/bag)	3740-6430	0-7

Note: All grouts were neat cement grouts except that used for beam 14, which was a natural sand grout (100 percent passing No. 30 sieve). All of the grouts contained a small amount of aluminum powder (1 to 3 g per bag of cement).

* One bag = 94 lb of cement = 42.6 kg (mass).

Table 2

General Information, Posttensioned Beams at Treat Island

(Installed June 1961)

Beam No.	Posttensioning System	Eccentricity of Tendon in.	Estimated Final Posttensioning Force, tons	Type of End Protection (See Note) Landward End	Seaward End
1*	A	0	23	Flush (1)	Ext (5)
2	A	0	23	Ext (4)	Ext (2)
3*	A	3	23	Ext (3)	Ext (1)
4	A	2	23	Ext (7)	Flush (7)
5	A	2	23	Ext (6)	Flush (6)
6*	A	1	23	Flush (9)	Ext (8)
7	B	0	26	Ext (1)	Flush (1)
8	B	2	26	Ext (2)	Ext (4)
9*	B	3	26	Ext (3)	Ext (5)
10	B	3	26	Flush (6)	Ext (6)
11*	B	1	26	Flush (7)	Ext (7)
12	B	1	26	Ext (8)	Flush (9)
13*	C	0	30	Ext (1)	Ext (3)
14	C	1	30	Ext (2)	Ext (4)
15*	C	3	30	Ext (5)	Ext (6)
16	C	2	30	Ext (7)	Ext (8)
17	D	3	42	Ext (1)	Ext (3)
18	D	0	42	Ext (4)	Ext (2)
19*	D	2	42	Ext (5)	Ext (6)
20	D	1	42	Ext (8)	Ext (7)

Note: Concrete placed against a cold joint with no surface treatment and no reinforcement (Ext (1) and Flush (1)).
Concrete placed against a cold joint with no surface treatment but with reinforcement (Ext (2)).
Concrete placed against a bush-hammered surface and with no reinforcement (Ext (3)).
Concrete placed against a bush-hammered surface but with reinforcement (Ext (4)).
Concrete placed against a surface that had been treated with a retarding agent and no reinforcement (Ext (5)).
Concrete bonded to the ends of the beam with an epoxy adhesive and no reinforcement (Ext (6) and Flush (6)).
Epoxy concrete without reinforcement (Ext (7) and Flush (7)).
Epoxy concrete with reinforcement (Ext (8)).
Sand-cement mortar with aluminum powder additive, comparatively dry and well tamped (Flush (9)).

* Beams were examined in the laboratory. The tendon in beam 13 was found to be unbonded and coated (not grouted).

Table 3

Posttensioning Systems Used

System	No. of Beams Tested	Type of Tendon	Method of Anchoring	Initial Posttensioning Force, tons	Estimated Final Posttensioning Force, tons
A	3	12 steel wires (each 0.196-in. diam)	Wedge action	42	23
B	2	1 steel bar (7/8-in. diam)	Direct bearing	35	26
C	2*	8 steel wires (each 1/4-in. diam)	Direct bearing	35	30
D	1	12 steel wires (each 1/4-in. diam)	Direct bearing	50	42

* One of these tendons was unbonded and coated with a mineral grease (beam 13).

Table 4

Twelve Types of End Anchorage Protection Used for Posttensioned Beams

Type No.	Designation*	End Anchorage Protection: Protective Material Used	Beam End Surface Treatment	Steel Reinforcement	No. of Beam Ends
1	Ext (1)	Air-entrained concrete	None, cold joint	No	4
2	Flush (1)	Air-entrained concrete	None, cold joint	No	2
3	Ext (2)	Air-entrained concrete	None, cold joint	Yes	4
4	Ext (3)	Air-entrained concrete	Bush-hammered	No	4
5	Ext (4)	Air-entrained concrete	Bush-hammered	Yes	4
6	Ext (5)	Air-entrained concrete	Retarded	No	4
7	Ext (6)	Air-entrained concrete	Epoxy-coated (sandblasted)	No	4
8	Flush (6)	Air-entrained concrete	Epoxy-coated (sandblasted)	No	2
9	Ext (7)	Epoxy concrete	Sandblast and primer	No	4
10	Flush (7)	Epoxy concrete	Sandblast and primer	No	2
11	Ext (8)	Epoxy concrete	Sandblast and primer	Yes	4
12	Flush (9)	Sand-cement mortar (with aluminum powder)	Sandblasted	No	2
				Total beam ends	40

* See Table 2.

Table 5

Summary of Thermal Expansion Values for Beam 20

Anchor Pair	Gage Reading at 40^o F	Gage Reading at 120^o F	ΔR $R_{120} - R_{40}$	ΔL $\frac{\Delta R}{2} \times 0.0001$ in.	L_o in.	Thermal Expansion Coefficient 10^{-6}/deg F
			Cycle No. 1			
S_1	388	445	57	0.0029	1.98	18.3
S_2	699	751	52	0.0026	2.00	16.3
S_3	762	770	8	0.0004	2.00	2.5
S_4	415	428	13	0.0007	1.98	4.4
L_1	1228	1248	20	0.0010	2.02	6.2
L_2	1031	1060	29	0.0015	2.01	9.3
L_3	888	898	10	0.0005	2.01	3.1
L_4	511	529	18	0.0009	1.99	5.7
			Cycle No. 2			
S_1	386	463	77	0.0039	1.98	24.6
S_2	681	745	64	0.0032	2.00	20.0
S_3	760	772	12	0.0006	2.00	3.8
S_4	396	426	30	0.0015	1.98	9.5
L_1	1235	1246	11	0.0006	2.02	3.7
L_2	1032	1049	17	0.0009	2.01	5.6
L_3	880	891	11	0.0006	2.01	3.7
L_4	502	519	17	0.0009	1.99	5.7

Photo 1. Landward end anchorage of beam 4 showing very little corrosion

Photo 2. Seaward end anchorage of beam 4 showing heavy corrosion and deterioration

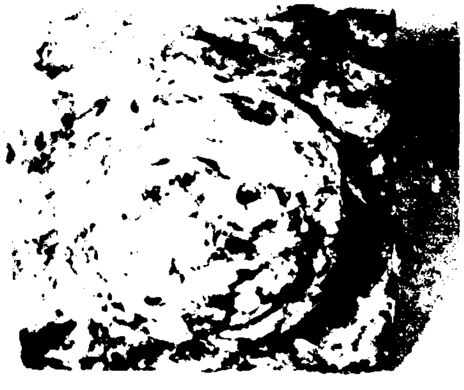

Photo 3. Landward end anchorage of beam 17 showing heavy corrosion. Note unsound, rusted metal flaking off

Photo 4. Inside surface of landward funnel housing of beam 17 showing heavy rust concentrated on bottom

Photo 5. Inside surface of seaward section of conduit of beam 17 showing rust concentrated along bottom, extending 1 ft from end

Photo 6. Outside surface of seaward end funnel housing of beam 17 showing heavy rusting with some steel corroding in flakes

Photo 7. Inside surface of seaward end funnel housing of beam 17 showing two streaks of rust extending along bottom

Photo 8. Twelve wires of beam 17 showing heavy rusting on landward ends

Photo 9. Seaward anchorage of beam 17 showing heavy corrosion

Photo 10. Landward end of beam 20 with a 1/2-in.-wide and 1/2-in.-deep gap separating end cap from beam proper

Photo 11. Seaward end of beam 20 with 1/2-in.-wide and 4- to 8-in.-deep gap separating end cap from beam proper

Photo 12. Landward end anchorage of beam 20 showing heavy corrosion

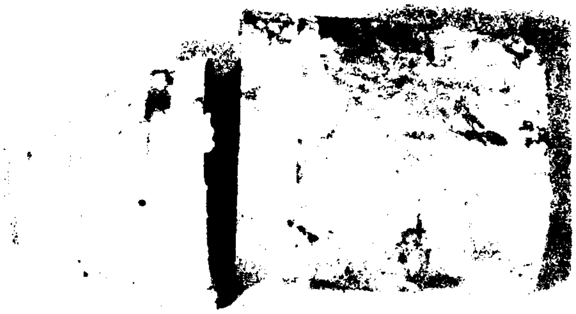

Photo 13. Outside surface of landward funnel housing of beam 20 showing heavy corrosion

Photo 14. Inside surface of landward funnel housing of beam 20 showing light rusting on bottom

Photo 15. Outside surface of middle section of conduit from beam 20 showing moderate rusting and heavy tarnishing. Note some rust areas with flaking steel

Photo 16. Outside surface of seaward funnel housing of beam 20 showing heavy corrosion

Photo 17. Inside surface of seaward funnel housing of beam 20 showing rust along bottom

Photo 18. Seaward end anchorage of beam 20 showing heavy corrosion. Note flaking of steel over surface area

Photo 21. Stirrup of beam 20 showing rust around weld point

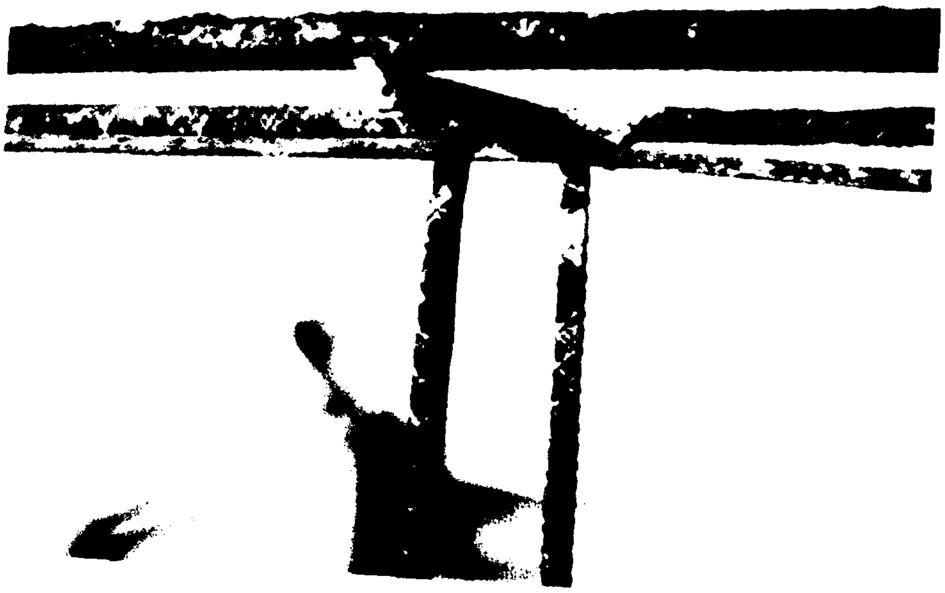

Photo 22. Stirrup of beam 4 showing spot of light surface rust

Photo 19. Stirrup of beam 4 showing rust around weld point

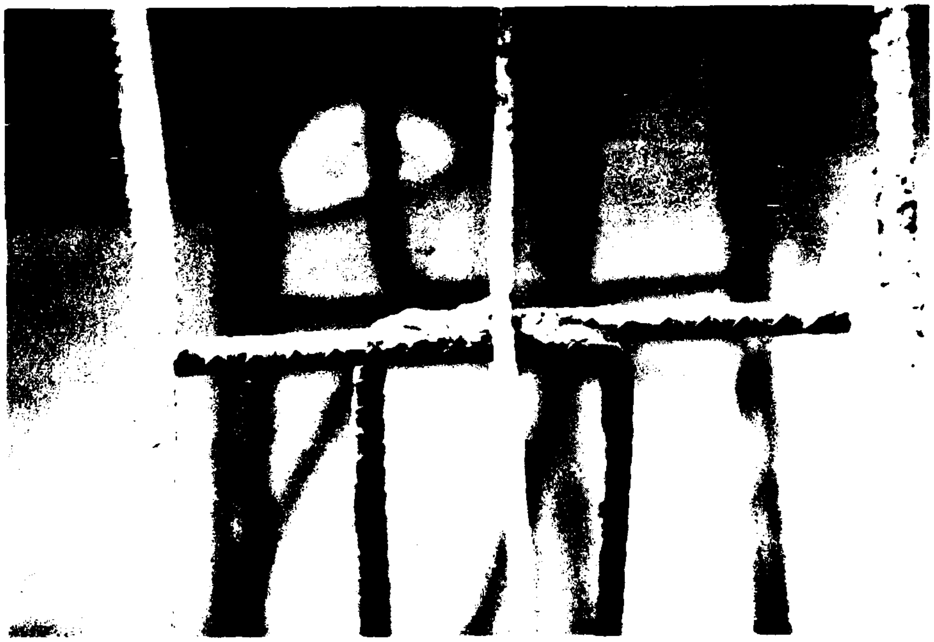

Photo 20. Stirrup of beam 17 showing rust around weld point

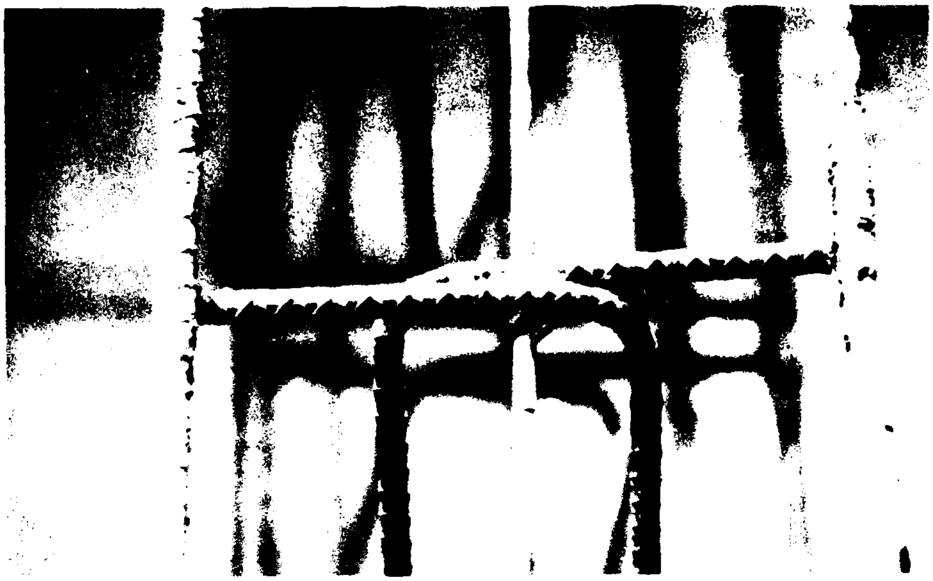

Photo 19. Stirrup of beam 4 showing rust around weld point

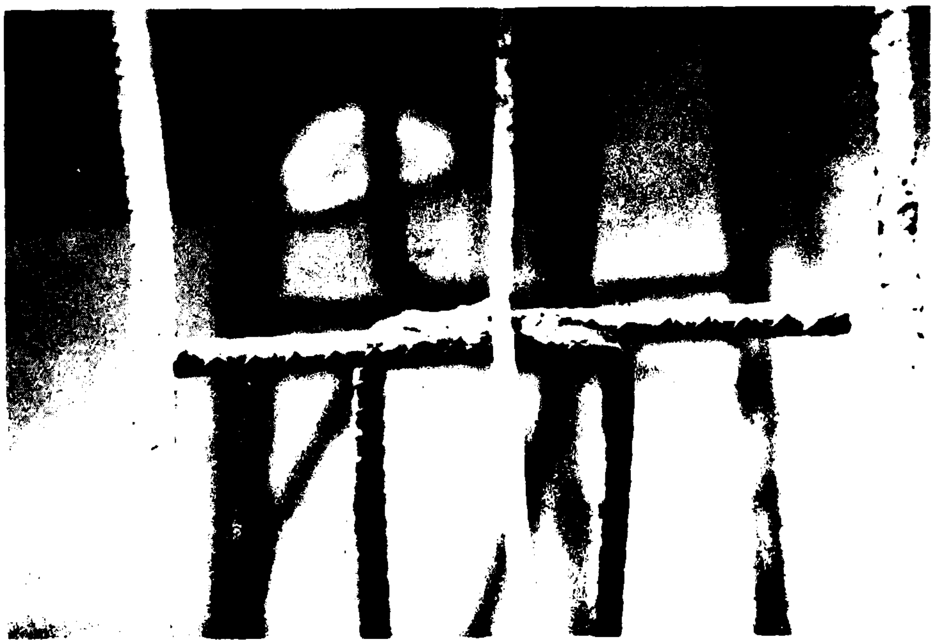

Photo 20. Stirrup of beam 17 showing rust around weld point

Photo 21. Stirrup of beam 20 showing rust around weld point

Photo 22. Stirrup of beam 4 showing spot of light surface rust

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